

LETTER TO THE EDITOR

ALMA Observations of Anisotropic Dust Mass-loss in the Inner Circumstellar Environment of the Red Supergiant VY CMa

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ABSTRACT

The processes leading to dust formation and the subsequent role it plays in driving mass-loss in cool evolved stars is an area of intense study. Here, we present high resolution ALMA Science Verification data of the continuum emission around the highly evolved oxygen-rich red supergiant VY CMa. These data enable us to study the dust in its inner circumstellar environment at a spatial resolution of 129 mas at 321 GHz and 59 mas at 658 GHz, allowing us to trace dust on spatial scales down to 11 R_* (71 AU). Two prominent dust components are detected and resolved. The brightest dust component, C, is located 334 mas (61 R_*) south-east of the star and has a dust mass of at least $2.5 \times 10^{-4} M_\odot$. It has an emissivity spectral index of $\beta = -0.1$ at its peak, implying that it is either optically thick at these frequencies with a cool core of $T_d \lesssim 100$ K, and/or contains very large dust grains. Interestingly, not a single molecule in the ALMA data has emission close to the peak of this massive dust clump. The other main dust component, VY, is located at the position of the star and contains a total dust mass of $4.0 \times 10^{-5} M_\odot$. It also contains a weaker dust feature extending over 60 R_* to the north with the total component having a typical emissivity spectral index of $\beta = 0.7$. We find that $> 17\%$ of the dust mass around VY CMa is located in clumps ejected within a more quiescent roughly spherical stellar wind, with a quiescent dust mass loss rate of $5 \times 10^{-6} M_\odot \text{ yr}^{-1}$. The observations suggest a continuous preferentially directed mass-loss from the star over many decades and do not support current models of convective driven only mass loss in red supergiant stars. We thus suggest other forces, i.e., MHD disturbances, are also needed to explain the observations.

Key words. Stars: supergiants – Stars: individual: VY CMa – Stars: mass-loss – Dust: stars

1. Introduction

Cool evolved stars are the main producers of dust in galaxies and are important drivers for the chemical evolution of matter in the Universe. Despite the importance of dust in a broad range of astrophysical phenomena, the conditions which lead to its formation in the outflows of evolved stars and its subsequent role in driving mass-loss remain largely unknown. Oxygen-rich red supergiants (RSGs) are sources of inorganic dust (silicate and alumina) which is formed and plays a role in launching mass-loss in the inner circumstellar environment of these stars. However, the dust properties in this region such as density, composition, and morphology have remained largely unknown due to a lack of spatial resolution.

A prime target to study the properties of dust around evolved stars is the enigmatic oxygen-rich RSG VY Canis Majoris (VY CMa). VY CMa is a late-M spectral type (M2.5-M5e Ia; Wallerstein 1958) RSG with an extremely large mass-loss rate ($\dot{M} \sim 2 - 4 \times 10^{-4} M_\odot \text{ yr}^{-1}$; Danchi et al. 1994). This is about two orders of magnitude greater than the well known early-M spectral type RSGs, Betelgeuse and Antares. Consequently, VY CMa has a highly dense and dusty circumstellar envelope which obscures it and produces a reflection nebula at optical wavelengths (Humphreys et al. 2007). Due to its relative proximity ($d = 1.2^{+0.13}_{-0.1}$ kpc; Zhang et al. 2012) and high intrinsic luminosity ($L = 3 \times 10^5 L_\odot$ using the photometry of Smith et al., 2001), the dust emission from the circumstellar envelope around VY

CMa has been studied from optical to centimeter wavelengths (e.g., Lipsy et al. 2005; Muller et al. 2007). The dusty envelope consists of a diffuse and extended region with loops and arcs expanding over several arc seconds through a more uniform medium. At the level of several tens of mas the envelope consists of a dense and dusty central core of which little is known about. It is within this region that the dust condenses and mass-loss is initiated by radiation pressure on the dust and subsequent drag on the gas species. In this Letter we report the results of a sub-100 mas study of this region using ALMA Science Verification data.

2. Observations and results

VY CMa was observed at 321 GHz, 325 GHz, and 658 GHz as part of the ALMA Science Verification process on 2013 16-19 August, using 16-20 antennas of the main array with projected baselines ranging from 14 m to 2.7 km. Details of the observations and data processing are provided in (Richards et al. 2014, hereafter R+14). For the purpose of the continuum analysis, we used a total of 1.74 GHz line free continuum channels around 321 GHz and 0.4 GHz centered around 658 GHz. As the data around 325 GHz provided similar results as the 321 GHz data, but were affected by the 325.15 GHz atmospheric water line resulting in increased noise, these data were not included in our subsequent analysis. The synthesized beam size, rms noise level, maximum recoverable scale (MRS), and total flux of the two observing bands are given in Table 1. Note that the rms noise

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Table 1. ALMA Continuum Observations of VY CMa.

ν (GHz)	Synthesized Beam ("×", P.A.)	rms noise (mJy beam ⁻¹)	MRS (")	Total S_ν (mJy)
321	$0.229 \times 0.129, 28^\circ$	0.6	8.3	587
658	$0.110 \times 0.059, 30^\circ$	6	4.0	3017

is non-uniform across the field, likely because of low-surface brightness and resolved out emission (see below). In Table 1 we report the rms in the region of maximum noise level, while in R+14 the rms corresponds to the lower rms areas.

The 321 GHz image along with the position corrected 658 GHz image are plotted in white and black contours in Figure 1, respectively. Continuous emission was detected above the $3\sigma_{\text{rms}}$ level on scales as large as $1.4''$ at 321 GHz and $0.8''$ at 658 GHz. There are two prominent components and an extended north north-east arc that are reproduced at both frequencies as seen in Figure 1. The position around the peak of the secondary component has recently been shown to coincide with the centre of expansion of many maser emission lines and has been deduced to be the location of the star (R+14). This component (VY) connects to the weaker emission extending for ~ 800 mas at a P.A. of $\sim 20^\circ$ which may contain some further substructure. Interestingly, the brightest component in both images (C) is not at the location of the star itself but is located 334 mas south-east of the star in the plane of the sky. Using a distance of 1.2 kpc to VY CMa, this angular distance corresponds to 400 AU, or $61 R_\star$ if a linear radius of $1420 R_\odot$ (at $2 \mu\text{m}$) is adopted (Wittkowski, 2012). R+14 have found that the 658 GHz masers, emitted out to ~ 240 AU, straddle this main continuum component and so the projected distance between this component and the star is unlikely to be much greater than the actual distance.

We fitted 2-D elliptical Gaussian components to the two main continuum features and found that both the C and the VY components were resolved at both frequencies. The sizes and flux densities of these components were estimated from the deconvolved fits and are listed in Table 2. The main C component is highly elongated at both frequencies in the south-east direction, with a major-to-minor axis ratio, $\theta_{\text{maj}}/\theta_{\text{min}} = 1.6 \pm 0.2$ at 321 GHz and $\theta_{\text{maj}}/\theta_{\text{min}} = 2.1 \pm 0.1$ at 658 GHz. We find that the size of component C is consistent at both frequencies within their errors. Because the 658 GHz image has less sensitivity to extended emission than the 321 GHz image, but the component has the same size in both images, we conclude that we do not resolve-out any of the emission from the C component. Comparing Tables 1 and 2, we can see that 50% and 60% of the total continuum flux density emanates from the main C component at 321 GHz and 658 GHz, respectively. The other main continuum component VY, is also resolved at both frequencies. It is elongated towards the north with $\theta_{\text{maj}}/\theta_{\text{min}} = 1.5 \pm 0.4$ at 321 GHz and $\theta_{\text{maj}}/\theta_{\text{min}} = 2.1 \pm 0.5$ at 658 GHz, with emission extending to $27 R_\star$ (180 AU). It is centered at the location of the stellar photosphere and therefore includes emission from the star itself at these sub-millimeter frequencies (see Appendix C). The VY component contributes about 26% and 17% of the total ALMA continuum flux density at 321 GHz and 658 GHz, respectively. The significant difference in size at the two frequencies is likely not to be due to the MRS at these small angular scales, but is probably due to a combination of different sensitivities to low surface brightness emission and the fact that the higher frequencies probe emission from hotter regions of VY.

A spectral index map of the continuum emission was created after convolving the 658 GHz data with the synthesized beam

from the 321 GHz image, and re-gridding the convolved image to match the pixel scale of the 321 GHz image. The resulting spectral index map is represented by the color image in Figure 2 while the contour levels represent the convolved 658 GHz image. All data below the $6\sigma_{\text{rms}}$ noise level in the convolved 658 GHz image has been omitted from Figure 2. The middle region of the main continuum component C, has a spectral index of $\alpha \sim 1.9$ (where $S_\nu \propto \nu^\alpha$). The spectral index value around the second continuum, or VY, and most of the extended emission in the north-east direction has a spectral index of $\alpha \sim 2.7$. The statistical error on the spectral index due to random noise errors are of order < 0.2 in the $6\sigma_{\text{rms}}$ region and decrease to 0.05 at the peak region. The 658 GHz S/N is inferior to the 321 GHz S/N, so this error is dominated by the 658 GHz data. There is also a systematic absolute error of ~ 0.22 on the entire spectral index map based on the $\pm 15\%$ uncertainty of the absolute flux calibration (R+14). Note that the difference in spectral index between the pixel fluxes in the map and integrated fluxes in the table for component VY is a result of the difference in size. The integrated flux at 658 GHz corresponds to the flux from a smaller area that at 321 GHz as noted above.

3. Discussion and conclusions

3.1. Comparison with HST

The color image in Figure 1 is a *HST*/WFPC2 exposure of VY CMa taken with the F1042M filter (Smith et al. 2001). The data has been adjusted for proper motion using the values of Zhang et al. (2012) and it can be seen that the peak emission fits very well with the second main continuum component in the ALMA data, VY. The typical positional uncertainty rms in this *HST* image is 48 mas in RA and 146 mas in Dec, while the ALMA positional error is 35 mas, ruling out a correspondence between the C component in the ALMA images and the peak of the *HST* image. We can conclude that most of the escaping scattered light at optical wavelengths is emitted along the line of sight to the star itself. There is no evidence of the main C component in the *HST* image, likely because the *HST* emission does not trace dense dusty emission, but rather more tenuous regions in the circumstellar environment. Scattered light polarimetry with the *HST* does show a pronounced lower polarization towards the south-east of the star (Jones et al. 2007), potentially indicating enhanced obscuration along the direction between the star and component C.

The extended south-west emission component in the *HST* image, which may be a density cavity in the circumstellar environment formed by a previous episodic mass-loss event, has no detectable signature in our ALMA continuum images. The extended component ends in what is named the Southwest (SW) Clump in Smith et al. (2001) and Humphreys et al. (2007). This clump is thought to be related to an ejection event from the star and has been estimated to have a dust mass lower limit of $5 \times 10^{-5} M_\odot$ and a temperature between 80 – 210 K (Shenoy et al. 2013). However, we see no sign of this clump in the ALMA data. With our $3\sigma_{\text{rms}}$ limits, we rule out a mass $> 7 \times 10^{-6} M_\odot$ (for $T = 80$ K) or $> 3 \times 10^{-6} M_\odot$ (for $T = 210$ K). For the ALMA observations to be consistent with the lower limit estimates of Shenoy et al. (2013), the dust temperature would have to be < 20 K. The exact nature of the SW clump is thus not clear. We also find no further compact sub-millimetre emission in the larger $\sim 7''$ region of dust seen with the *HST*.

Table 2. Properties of the two main continuum components, C and VY.

ID _v	θ_{maj} (mas)	θ_{maj} (R _★)	θ_{min} (mas)	θ_{min} (R _★)	P.A. (°)	S_v (mJy)	α	β	T_d (K)	τ_v	M_d (M _☉)
C ₃₂₁	182 ± 13	33	117 ± 16	21	112 ± 10	348 ± 16	1.9	−0.1	450	0.19	2.5 × 10 ^{−4}
C ₆₅₈	206 ± 4	37	99 ± 3	18	115 ± 1	1532 ± 55	1.9	−0.1	450	0.17	1.6 × 10 ^{−4}
VY ₃₂₁	219 ± 19	40	144 ± 33	26	4 ± 17	155 ± 14	2.7	0.7	970	0.04	4.0 × 10 ^{−5}
VY ₆₅₈	150 ± 8	27	73 ± 17	13	22 ± 5	501 ± 53	2.7	0.7	970	0.02	1.8 × 10 ^{−5}

Notes. θ_{maj} and θ_{min} : Major and minor axes of the deconvolved components of the Gaussian fits to the continuum components. S_v : Integrated flux from the deconvolved fits. α : Spectral index. β : Emissivity spectral index. T_d : Dust temperature assuming isothermal and optically thin dust, which may not be the case for the C component. τ_v : Optical depth. M_d : Dust mass.

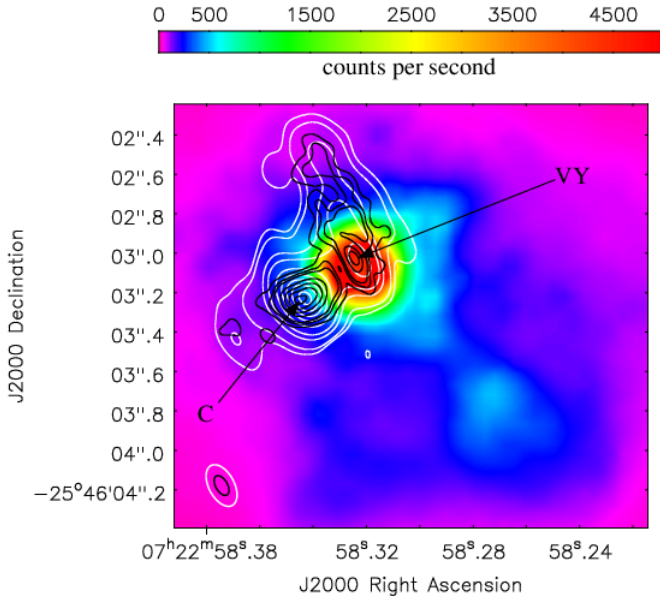


Fig. 1. The color image is a *HST*/WFPC2 exposure of VY CMa using the F1042M filter (Smith et al., 2001) corrected for proper motion. The data has been truncated at 5000 counts per second and scaled with a power cycle of -1.5 to highlight the extended emission in the south-west direction. The contours represent the ALMA data at 321 GHz (white) and 658 GHz (black) and the corresponding synthesized beams are located in the bottom left of the image. The 321 GHz contour levels are set at $[5, 10, 30, 50, 100, \dots, 300] \times \sigma_{\text{rms}}$, while the 658 GHz contour levels are set at $[3, 6, 9, 20, 30, 40, 50] \times \sigma_{\text{rms}}$.

3.2. Properties of the Dust

Dust is the main source of the observed thermal sub-millimeter emission around VY CMa. If the dust is optically thin at these frequencies and we assume the Rayleigh-Jeans approximation, then the observed flux density minus the stellar flux density contribution S_\star , is proportional to the mass of the emitting dust M_d , such that

$$S_v - S_\star = \frac{3M_d Q_v T_d k \nu^2}{2a_g \rho_g c^2 d^2} \quad (1)$$

where Q_v is the grain emissivity, a_g and ρ_g are the radius and mass density of the dust grains, respectively, d is the distance to the star, and T_d is the dust temperature (Knapp et al. 1993). Assuming that the grain emissivity has a power law dependence on frequency, $Q(\nu) \propto \nu^\beta$, the flux density is $S_v \propto \nu^\alpha$, where $\alpha = 2 + \beta$. Here, β is the dust emissivity spectral index and has typical values of $\beta = 1.8 \pm 0.2$ for both diffuse and dense

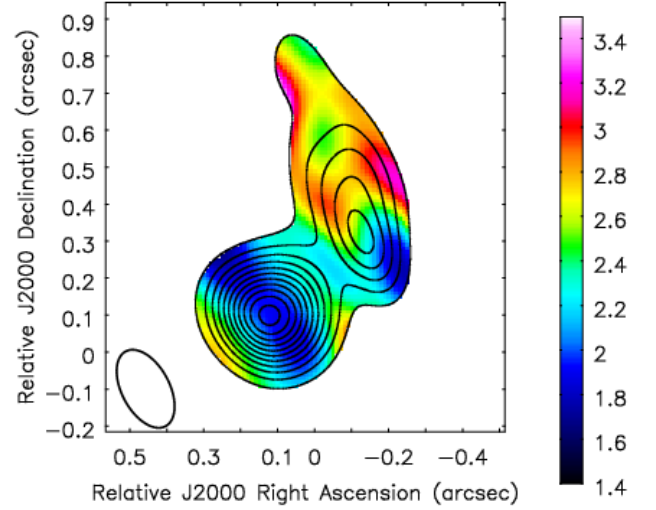


Fig. 2. The color image shows the spectral index map derived from the 321 GHz and 658 GHz ALMA continuum maps. The strongest continuum component has a spectral index $\alpha = 1.9 \pm 0.05$ at the peak while the weaker elongated emission has a typical spectral index $\alpha = 2.7 \pm 0.1$. The error values here do not include the systematic error based on the $\pm 15\%$ uncertainty of the absolute flux calibration, which is in the same direction for both regions of the image. The contour map represents the 658 GHz map which was convolved with the 321 GHz restoring beam to create the spectral index map. Contour levels are set at $[3, 6, 9, \dots, 39] \times \sigma_{\text{rms}}$.

clouds in the interstellar medium (Li & Draine 2001; Goldsmith et al. 1997). For evolved stars, the dust emissivity index is generally lower (Knapp et al. 1993), and for VY CMa previous observations have found values $\beta \sim 0 - 1.0$ (Shinnaga et al. 2004, Kamiński et al. 2013) while its circumstellar environment has been modelled using values of $\beta = 0.9$ (Knapp et al. 1993).

Our spectral index map in Figure 2 shows that the two spatially resolved continuum components in the inner circumstellar envelope have different spectral indices. The second brightest continuum component VY, has a typical dust emissivity index of $\beta = 0.7 \pm 0.1$ which is consistent with previous observations. However, much of the main continuum component C, has a dust emissivity index of $\beta = -0.1$ around the location of the peak emission, meaning that the sub-millimeter emission from this component is, or is close to becoming optically thick. Following Herman et al. (1986), optically thin dust at a radius r_d is heated by the incident stellar radiation field to a dust temperature

$$T_d = \left(\frac{L_\star T_\star^\beta}{16\pi\sigma r_d^2} \right)^{1/(4+\beta)} \quad (2)$$

where L_\star and T_\star are the stellar luminosity and temperature, respectively. Assuming $T_\star = 3490$ K (Wittkowski et al. 2012), the main continuum component, C, would have an isothermal temperature of 450 K at 400 AU from the star, while the VY component would have a value of 970 K at a mean dust radius of 67 AU. These rough estimates for the dust temperature allow us to empirically calculate the optical depth at both observing frequencies, the values of which are given in Table 2. The VY component is optically thin at both frequencies with $\tau_{321-658 \text{ GHz}} = 0.02 - 0.06$, while the main continuum component C, has an optical depth of $\tau_{321-658 \text{ GHz}} \sim 0.2$, and would become optically thick at 110 – 120 K at both frequencies. Therefore, a cooler dust component in the center of C would explain the spectral index having a lower value than expected for optically thin dust. Alternatively, larger dust grains could also result in small β values although our observing frequencies would then suggest that the dust grains would need to be much larger than 100 μm . Interestingly we find that the molecular emission lines from the ALMA data avoids the C component, consistent with the molecular emission offsets found in SMA observations (Muller et al. 2007; Kamiński et al. 2013).

Equation 1 can be re-arranged to find the total mass of dust in each of the two main continuum components. The main component C may not be fully optically thin at both frequencies and so its dust mass estimates will be lower limits. Following Knapp et al. (1993) we assume typical oxygen-rich star values for the radius and mass density of the dust grains, $a_g = 0.2 \mu\text{m}$ and $\rho_g = 3.5 \text{ g cm}^{-3}$. We slightly alter their grain emissivity function to include our derived dust emissivity spectral index so that $Q_\nu = 5.65 \times 10^{-4} (\nu/274.6 \text{ GHz})^{0.7}$. We also assume that the main C component has the same dust composition as VY, so the emissivity spectral index of C would also be $\beta = 0.7$ if fully optically thin. We then derive dust masses of $2.5 \times 10^{-4} M_\odot$ at 321 GHz and $1.6 \times 10^{-4} M_\odot$ at 658 GHz for the main dust component C, having assumed no photospheric contribution. The lower mass value at 658 GHz is probably due to a combination of optical depth effects and an inaccurate grain emissivity law. We derive dust masses of $4.0 \times 10^{-5} M_\odot$ at 321 GHz and $1.8 \times 10^{-5} M_\odot$ at 658 GHz for the VY component having subtracting the stellar contribution¹. The discrepancy in the dust mass values here is probably due to the different MRS at the two frequencies.

3.3. Dust Mass-Loss History and Mechanisms

Considering we find that part of the dust emission of VY CMA arises in compact clumps, we can obtain a new estimate of the average dust mass-loss rate by determining the dust mass that is resolved out in the ALMA observations. We assume the dust to be extended over the $\sim 8''$ size of the *HST* image, use an average dust velocity V_d which is dependent on grain size, and for VY CMA is $\sim 60 \text{ km s}^{-1}$ for grains of $\sim 0.25 \mu\text{m}$ (Decin et al. 2006), and take an average temperature of 200 K throughout the shell. The observed VY component arises from the dust lost in the last $\sim 20(V_d/60 \text{ km s}^{-1})$ yr and the resolved out emission ($\sim 1.1 \text{ Jy}$ at 321 GHz and $\sim 7.8 \text{ Jy}$ at 658 GHz) corresponds to the dust lost over $\sim 360(V_d/60 \text{ km s}^{-1})$ yr before. We find, for $\beta = 0.7$ using Eq. 1, a dust mass of $\sim 1.8 \times 10^{-3} M_\odot$ consistent at both frequencies, and a dust mass-loss rate of $5 \times 10^{-6} (V_d/60 \text{ km s}^{-1}) M_\odot \text{ yr}^{-1}$, two to five times larger than previously estimated by Sopka et al. (1989) and Knapp et al. (1993). Now taking all compact emission from the ALMA observations, with the exception of that around the star, to be in optically thin clumps at ~ 450 K, those

clumps contain $\sim 3 \times 10^{-4} M_\odot$ of dust. This is a lower limit, as there can be a significant component of cold dust, potentially present in C and in the SW and other *HST* features not detected by ALMA. We can thus conclude that $> 17\%$ of the dust mass around VY CMA is located in clumps ejected within a more quiescent roughly spherical stellar wind.

The action of large convective cells have been hypothesized to initiate mass-loss in RSGs (e.g., Lim et al. 1998). These convective cells are predicted to have time scales of ~ 150 days (Schwarzschild 1975) and are expected to eject material at random position angles from the star over time and generate supersonic motions and shocks (Lion et al. 2013). Our observations have revealed a massive dust clump with diameter $\sim 30 R_\star$ centered at $60 R_\star$ and a weaker continuous dust feature extending $90 R_\star$ to the north. The existence of these features imply continuous preferentially directed mass-loss from the star over many decades in contrast to what would be expected from a convective driven mass-loss only scenario. A mass-loss mechanism which is localized but much more stable over time is required to explain our observations. This would suggest a magnetic origin. Indeed a surface magnetic field strength of 10^3 G has been extrapolated from circumstellar maser measurements for VY CMA (Vlemmings et al. 2002). Cool spots on the photosphere due to localized long lived MHD disturbances could then enhance local dust formation, and hence drive mass-loss in the localized directions evident in our ALMA data.

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¹ See Appendix C

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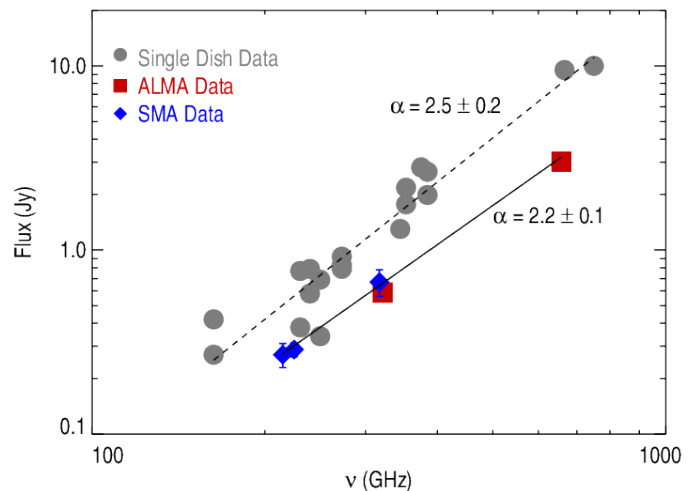


Fig. B.1. A compilation of the single dish bolometer and interferometric mm/sub-mm continuum observations of VY CMa. The dashed line indicates the spectral index fit to the single dish observations, with $\alpha = 2.5 \pm 0.2$, while the solid line is the fit to the interferometric observations, with $\alpha = 2.2 \pm 0.1$.

Appendix A: Position corrected offset

Uncertainties in the phase transfer of the data resulted in ~ 110 mas offsets between the main continuum peaks in the 321 and 658 GHz images. To find the optimal (RA, Dec)-offset correction, we shifted the 658 GHz image relative the 321 GHz image and computed a 2-D cross-correlation function for a range of shifts. The maximum correlation between the two images gave a $(-80 \text{ mas}, -30 \text{ mas})$ -offset correction for the 658 GHz image, similar to the correction found by R+14 when aligning the peak position of the second brightest continuum component.

Appendix B: Comparison with other (sub-)mm observations

There has been many previous (sub-)millimetre continuum flux measurements of VY CMa. In Fig. B.1, we present both the single dish observations, using the compilations of Knapp et al. (1993) and Ladjal et al. (2010), and the interferometric measurements from this paper and from SMA observations (Shinnaga et al. 2004; Muller et al. 2007; Kamiński et al. 2013). It is immediately apparent that the interferometric observations systematically underestimate the total flux. Additionally, the spectral index determined from the single dish observations ($\alpha = 2.5 \pm 0.2$) is larger than the one fitted to the interferometric observations ($\alpha = 2.2 \pm 0.1$). Both these differences can be attributed to flux that is resolved out by missing short baselines as well as having low surface brightness. As the shortest baselines of the ALMA and SMA observations are comparable, we can directly compare the fluxes measured at similar frequencies. But as the MRS at higher frequencies is smaller, more flux is resolved out resulting in a lower fitted spectral index. Assuming the true spectral index of the interferometric observations to be the same as that of the single dish observations and there are no significant changes of dust properties on the different scales, we can conclude that the ALMA observations loses $\sim 65\%$ of the emission at 321 GHz and $\sim 72\%$ of the emission at 658 GHz. Considering the MRS and sensitivity of the ALMA observations, most of the sub-millimetre dust continuum flux is thus located in a smooth low surface brightness distribution stretching beyond $\sim 4''$, which is consistent with the dust distribution seen over $\sim 7''$ with the *HST* (e.g., Smith et al. 2001).

Appendix C: Stellar flux contribution

The stellar flux contribution S_\star , needs to be considered when calculating the dust mass from the VY component at these

ALMA frequencies. Previous studies have estimated this contribution by calculating the flux of an optically thick black-body of radius R_\star and temperature T_{eff} . Estimating the contribution from this method yields $S_\star = 26.5 \text{ mJy}$ at 321 GHz and $S_\star = 111 \text{ mJy}$ at 658 GHz, where we have assumed a stellar radius of $R_\star = 1420 R_\odot$ (6.84 AU or 5.7 mas) and an effective temperature $T_{\text{eff}} = 3490 \text{ K}$ (Wittkowski et al. 2012). However, RSGs have weakly ionized extended atmospheres which will become opaque at (sub-)mm frequencies. To estimate this contribution at these ALMA frequencies, we scaled the Harper et al. (2001) semi-empirical model for the M2 Iab RSG Betelgeuse (without the silicate dust) to the angular diameter of VY CMa. The main source of opacity in this model is the H^- and H free-free opacity from electrons produced by photoionized metals. We then assumed the same ionization fraction and scaled the particle densities so that good agreement was obtained with the Very Large Array centimetre observations of VY CMa from Lipsy et al. (2005). The stellar contribution from this weakly ionized atmosphere is 36 mJy at 321 GHz and 124 mJy at 658 GHz.